Ádám Sódor

Blazhko Modulation of RR Lyrae stars

theses

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1. Precedings

RR Lyrae stars are important objets in many fields of astrophysics. They are important distance indicators on the distance scale of our Galaxy and the Local Group thanks to their characteristic light curves and moderately bright absolute magnitudes. This makes them an important step in the cosmic distance ladder. Due to their old ages, Galactic RR Lyrae stars are vitnesses of the young Milky Way. Their metallicity can easily be determined from the Fourier parameters describing the shape of their light curves according to empirical formulae. This makes them tracers of chemical evolution of different populations of stars. RR Lyrae variables are test objects of pulsation and evolution theories.

The general oppinion is that the physics of RR Lyrae stars are well known. Their internal structure can be determined by theories on the interior physical processes and on stellar evolution. Using pulsation models of stars corresponding to these theoretical structures of RR Lyrae stars, their observed light curves can be reproduced. It is known, however, for more than a century that several RR Lyrae stars change the shape of their light curves on time scales of tens of days. This phenomenon is named Blazhko effect, after one of its discoverer. Its physical explanation is not yet known. Earlier statistics indicated that 25–30 % of RRab stars and 1–5 % of RRc stars showed this effect. It is a minority, which, however, cannot be neglected.

We cannot know for sure that astrophysical results based on the physics of RR Lyrae stars, are correct indeed, until the physical origin of the Blazhko effect is known.

2. Scientific goals

In January 2004, we launched the Konkoly Blazhko Survey using the newly refurbished and automatised 60 cm Heyde–Zeiss reflector of Konkoly Observatory at Sváb-hegy. Our scientific goal was to advance our understanding of the physics of the Blazhko effect. Even the basic photometric observations of Blazhko variables were deficient; at the beginning of our survey, there was not any extended Blazhko light curve that covered completely the phases of both the pulsation and the modulation. Consequently, there were no extensive data that showed the appearance of the modulation in detail for Blazhko models to describe.

Our principal goal was therefore to study how modulation appears in the light curves. By studying multicolour Blazhko light curves, we expect to gain information on the changes in global physical parameters during the modulation cycle. A further goal of our survey is to study the incidence rate of the modulation among RR Lyrae stars in an appropriately large and homogeneous sample.

3. Methods

The first step in processing the CCD photometric observations is the reduction, when the object frames are calibrated using technical CCD frames. After calibration, the brightness of the stars we are interested in, can be measured. With this, the photometric time series, the light curves, are available.

The archive photograpic and photoelectic observations were processed by the special reduction and photometric methods needed.

We are looking for a mathematical description of the light curve as a sum of harmonic functions. The periodicities present in the light curve are studied by Fourier analysis. The Fourier spectrum contains aliases due to the nature of the observational data sampling. Therefore the solution is sought by successive approximation steps, with more and more frequencies identified. Among the strongest spectral peaks true signals are sought. Then a fit to the original data is made with all the frequencies identified so far. The fitted curve is subtracted from the data and the loop continues until any significant peak in the residual spectrum remains. The light variation of RR Lyrae stars can be described with several linearly independent frequencies and many of their harmonics and linear combinations.[1] Identifying these, the light curve's mathematical description is found.

Another important tool for studying RR Lyrae light curves is the $O-C$ analysis. This method studies the times of light maxima or the times of any other well defined point of the light curve. These times are then compared to a corresponding calculated value. For the calculation usually constant period, or in some cases linear period change is assumed. O stands for observed, C for calculated times. Variations in pulsation period and the modulations in the pulsation phase can be studied by means of the $O-C$ diagram. As a result of the light-time effect, $O-C$ analysis is feasible to detect the presence of a companion as well. However, up to now no binary membership of any RR Lyrae has been proven beyond doubt.

Many special data processing demands, which arose during my scientific work, required unique solutions. Since there are often no softwares available for these purposes, it is a must to develop my own scripts and programs from time to time.

[1] Single mode (RRab or RRc) stars show only one base frequency and many of its harmonics. Double mode (RRd) stars show both the fundamental mode frequency and the first overtone one and their harmonics and linear combinations. In Blazhko stars the pulsation frequency and the modulation frequency (frequencies) are the base frequencies and many of their linear combinations appear.

4. Theses

4.1. Studying RR Lyrae stars

I. I have been taking part in the obervations, data reduction and analysis of the Konkoly Blazhko Survey (KBS) since its beginning in january 2004. I made observations on about 200 nights, mainly of RR Lyrae stars. I developed many scripts and programs to make the observations, data reduction and light curve analysis easier.

In the frame of the survey, 30 short period ($P < 0.5$ d) RRab have been observed and studied. In this sample, 14 stars are unambiguously modulated while 16 shows no significant light curve changes. The KBS provided the first multicolour observations of Blazhko stars that covered both the pulsation and modulation cycles completely.

The nearly 50 per cent incidence rate of the modulation in the KBS sample is far greater than the 25–30 per cent frequency found by earlier investigators. These studies were, however, not accurate enough to detect modulations weaker than 0.1 mag change in maximum brightness. The high ratio of light curve modulation in the KBS is most likely due to the 7 stars showing modulations weaker than 0.1 mag in maximum brightness. Presumably, there are Blazhko stars with even weaker modulation also, which cannot be detected with our instrument. Therefore, the nearly 50 per cent ratio we have found, is only an underestimate of the true incidence rate of the modulation. I have shown that the modulation strength of RR Gem changed on time scales of several years. There was even an observation period when no modulation showed up (see thesis no. II.). This finding warns us that there might be Blazhko stars that have modulation below the detection limit at the time of the observation, while, at an earlier or later epoch, they would appear to be modulated. Therefore, the number of Blazhko stars may be even larger. [5]

4.2. The modulation of RR Geminorum on a long term scale

II. I have been taking part in the observaions and analysis of the fundamental mode RR Lyrae star RR Gem in 2004–2005. This star showed modulation with about 40 d period in the 1930s, during the photographic observations obtained at the Konkoly Observatory, while the modulation vanished for the 1950s, according to the photoelectric observations (László Detre 1970, Transactions of the IAU XIV A. Reports on Astronomy, 259). Since that time, the variable was considered as an unmodulated RRab star.

Our observations provided extended and accurate multicolour CCD light curves on RR Gem. The analysis of these data revealed that RR Gem showed weak but definite modulation during this interval. The maximum brightness in V band changed less than 0.1 mag during its 7.2 d modulation cycle. There was no RR Lyrae star with similarly weak modulation and with such a short Blazhko period in 2004.

Scientists of the Konkoly Observatory regularly observed RR Gem since 1935. Analysing these unpublished data, I studied the long term variations in the pulsation and modulation of this variable. I digitised and re-reduced the archive photographic plates, exposed between 1935 and 1953. The photoelectric data were provided in reduced form by Béla Szeidl. The analysis of the light curves from different intervals revealed that the strength and character of the modulation changed significantly during the studied 80 years long interval. During the first part of the photograhic observations, the modulation was stronger than today, with about 0.2 mag maximum brightness variation, which was accompanied with strong phase modulation of the rising branch. The phase modulation weakened later, while the strenght of amplitude modulation changed also. At the begining of the photoelectric observations the modulation was undetectably weak, perhaps it even ceased then. This is the first evidence that the modulation might be temporal. I have detected small changes in the modulation period also, which changed in correlation with the period of pulsation. [3, 4, 8]

III. In the middle of the photographic observations of RR Gem, a significant and sudden change in the pulsation amplitude occurred. At this time, the properties of the modulation and pulsation changed along with the pulsation amplitude, which was unambiguously detected notwithstandig the poorer accuracy of the photographic observations. This is the first observational evidence of change in the pulsation amplitude of an RR Lyrae star. According to the $O-C$ diagram shows that this change had to happen in a very short interval. The change itself has not been observed, but the run of the $O-C$ data of the observed maxima imposes an upper limit on this duration. Therefore, I conclude that these changes happened within 100–200 days. The relative change in the period is $\Delta P/P = 1.6 \cdot 10^{-4}$, which isparticularly large, especially within such a short interval, but it is not unexampled. The sudden period change indicates changes in the stellar structure, which affected not only the pulsation but the modulation strength also. It is worth to note that another Blazhko star from the KBS sample, RY Comae, also showed a sudden change in the mean pulsation amplitude during our CCD observations. This well-documented change happened within less than a week. The change in the pulsation amplitude was accompanied by changes in the modulation properties in this case also. [3, 4]

4.3. Light curve modulation of other Blazhko stars

IV. As a preparatory work for the KBS, I revised the modulation of the known Blazhko stars. These variables were first collected by Béla Szeidl (1988, in Multimode Stellar Pulsation, ed. G. Kovács, L. Szabados and B. Szeidl, Kultúra, Budapest, p. 45). This list was updated by Horace Smith (1995, RR Lyrae Stars, Cambridge University Press). This latter list contains altogether 43 RRab and 3 RRc stars. From one hand, the original data – if they were available – were Fourier analysed, which usually was not feasible at the time of the original publication. On the other hand, the published modulation period was sought in the objects' light curves from the databases of the NSVS and ASAS surveys. Our investigation showed that the modulation period or even the modulation itself was questionable for 10 objects. Two stars out of these 10 were later observed during the KBS (MW Lyr and DM Cyg). Our results proved that the suspicion was appropriate. Althoug both stars were found to be modulated, both with periods and strengths different from the originally claimed values. The modulation of DM Cyg is so weak that is surely undetectable by visual observations. [1, 11, 15]

V. Our multicolour observations with the 60 cm telescope at Sváb-hegy on SS Cancri revealed that this star shows the Blazhko effect. The modulation of SS Cnc is similarly weak as that of RR Gem, with an even shorter period of 5.3 d. There are many similarities but there are also differences between the modulation properties of the two stars. While at RR Gem, only the minimum and maximum brightnesses are modulated, at SS Cnc, the phases of the rising branch and light maximum also change. The modulation affects a wider pulsation phase range in SS Cnc than in RR Gem. Differences appear also between the Fourier spectra of the two stars. The amplitudes of the modulation sidelobes of SS Cnc are more asymmetric. The lower frequency components of the frequency triplets ($kf_0 - f_\mathrm{m}$) have much larger amplitudes than the higher frequency ones ($kf_0 + f_\mathrm{m}$). [9]

VI. I have pointed out that the CCD light curves we obtained on UZ Ursae Maioris showed modulation, which could not be desribed with only one modulation frequency with the observational accuracy. This variable seems to be modulated with more than one periods. The second periodicity we have found is near to the length of the time series. Therefore it cannot be decided wether this frequency describes a periodic variation indeed. [2]

VII. I observed MW Lyrae with my colleagues in 2006–07, through two observing seasons in the frame of the KBS by the 60 cm telescope. The light curves of MW Lyr show strong features of modulation with a period of 16.5 d. During the modulation cycle, the pulsation amplitude increases nearly twofold then it decreases again, while the phases of the minimum light, the rising branch and the maximum brightness are also modulated strongly. The Fourier spectra of MW Lyr show not only $\pm f_{\mathrm{m}}$ modulation components around the pulsation harmonics (triplet), but $\pm 2f_{\mathrm{m}}$ (quintuplet) and $\pm 4f_{\mathrm{m}}$ (septuplet) peaks can also be found. The residual spectrum shows peaks even after the removal of these multiplets. Amongst others, modulation peaks with $\pm 12.5f_{\mathrm{m}}$ separation also appear. After prewhitening the residual with 30 additional frequencies, the remaining signal is still significantly larger than the observational uncertainity. It suggests that a part of the light variation of MW Lyr is not periodic, most probably the modulation has a stochastic or chaotic component, too. [11]

4.4. Inverse Photometric Baade–Wesselink analysis

VIII. Average colours of RR Lyrae variables calculated from multicolour light curves are ambiguous, hence, they are not appropriate for determining the physical parameters of these stars. Therefore, I developed a new Inverse Photometric Baade–Wesselink (BW) method (IP method), which is capable to derive physical parameters (effective surface temperature – T_{eff}, luminosity – L, radius – R) and their changes with time excluseively from multicolour light curves. The main advantage of this method is that no spectroscopic observations are needed to provide radial velocity data.

The IP method, using a nonlinear least squares algorithm, searches for the effective temperature (T_{eff}) and pulsational velocity (V_{p}) curves, the distance and the mean radius that best fit the observed light curves in all photometric bands, utilising synthetic colours and bolometric corrections from static atmosphere models.

The method was tested on 9 RRab stars subjected to Baade-Wesselink analyses earlier by several authors. The physical parameters derived by our method are well within their possible ranges defined by direct Baade-Wesselink techniques when used with good quality VI_{C} or BVI_{C} light curves. I have also shown that with appropriately good quality light curves, even without knowing the colour zero points, good resuts are obtained, fitting these values also. [7]

IX. As part of the development of the IP method, I have shown that the pulsational velocity curve of RRab stars correlate well with their I_{C} light curve. The relation between the two curves was presented as a 7th order polynomial. Tianxing Liu (1991, PASP, 103, 205) published a template pulsational velocity curve of RRab stars earlier. My relation gives somewhat better results in most phases, except on the descending branch where my formula is substantially better. Further advantage of my formula is that for a Blazhko star, it gives different pulsational velocity curve shapes for different modulation phases, which might be a better approximation of the reality than the fixed shape of Liu's template. [7]

X. During the development of the IP method, I payed special attention to its applicability for Blazhko RR Lyrae stars. There is no simultaneous pulsational velocity measurements with photometric observations of any Blazhko star that appropriately covers both the pulsation and modulation phases. Therefore, the effect of the modulation on the global physical parameters could not yet be studied by spectroscopic BW analysis. The IP method proved to be capable to inspect the strong modulation of MW Lyr. The investigation showed that MW Lyr is cooler with $\sim$50 K, larger by $\sim 0.04\,R_\odot$ and more luminous with $\sim 1\,L_\odot$ in large amplitude phase than at small pulsation amplitudes. This is the first time when changes with modulation phase in the physical parameters of a Blazhko star are derived. [14]

XI. After the strongly modulated MW Lyr with known colour zero points, I applied the IP method on DM Cyg, the Blazhko star of the KBS with the weakest modulation. Here the unknown colour zero points imposed further complications. Notwithstandig, the IP method proved to be applicable in this case also. Our results show that the physical parameters of DM Cyg change similarly to that of MW Lyr but with a much lower amplitude, in line with the much weaker modulation. [15]

XII. In the frame of the KBS, 16 non-modulated RRab stars were observed. Their multicolour light curves have been published. The measurements were made in 2–4 photometric bands (using VI_C, BVI_C or $BVR_\mathrm{C}I_\mathrm{C}$ filters), with good photometric accuracy and good phase coverage. The photometric metallicity of all the 16 objects were determined, based on their light curve parameters. I intend to study these variables with the IP method in the near future. [6, 10, 12, 13, 16]

5. Conclusions

The Konkoly Blazhko Survey provided extended and accurate multicolour light curves on 30 RRab stars and 14 Blazhko stars among these. The scientific aims were partly fulfilled, however, there are a lot additional work to do.

Many aspects of the light curve modulation has been revealed; its temporal behaviour, multiperiodicity, frequency structure. Changes in the mean physical parameters with modulation were also revealed. The occurrence rate of the modulation turned out to be much higher than it was suspected earlier.

The fact that the physical origin of the Blazhko phenomenon remained unclear, gives us further tasks.

Publications on the theses

Single- and first author papers

1. **Sódor, Á.**, Jurcsik, J. 2005, IBVS, 5641: „Revision of the List of Galactic Field RRab Stars with Known Blazhko Periods"

2. **Sódor, Á.**, Vida, K., Jurcsik, J., Váradi, M., Szeidl, B., Hurta, Zs., Dékány, I., Posztobányi, K., Vityi, N., Szing, A., Kuti, A., Lakatos, J., Nagy, I., Dobos, V. 2006, IBVS, 5705 „UZ UMa: An RRab star with double-periodic modulation"

3. **Sódor, Á.** 2006, PADEU, 17, 115: „The long term behaviour of RR Gem"

4. **Sódor, Á.**, Szeidl, B., Jurcsik, J. 2007, A&A, 469, 1033: „The Blazhko behaviour of RR Geminorum II, Long-term photometric results"

5. **Sódor, Á.** 2007, AN, 328, 829: „Studying Blazhko RR Lyrae stars with the 24-inch telescope of the Konkoly Observatory"

6. **Sódor, Á.**, Jurcsik, J., Nagy, I., Váradi, M., Dékány, I., Vida, K., Hurta, Zs., Posztobányi, K., Vityi, N., Szing, A., Dobos, V., Kuti, A. 2007, IBVS, 5793: „Multicolour CCD Photometry of Three RRab Stars"

7. **Sódor, Á.**, Jurcsik, J., Szeidl, B. 2008, MNRAS, közlésre elfogadva: „A new method for determining physical parameters of fundamental mode RR Lyrae stars from multicolour light curves"

Further papers

8. Jurcsik, J., **Sódor, Á.**, Váradi, M., Szeidl, B., Washüttl, A., M. Weber, I. Dékány, Zs. Hurta, B. Lakatos, K. Posztobányi, A. Szing, and K. Vida 2005, A&A, 430, 1049: „The Blazhko behaviour of RR Geminorum I, CCD photometric results in 2004"

9. Jurcsik, J., Szeidl, B., **Sódor, Á.**, Dékány, I., Hurta, Zs., Posztobányi, K., Vida, K., Váradi, M., Szing, A. 2006, AJ, 132, 61: „The shortest modulation period Blazhko RR Lyrae star: SS Cnc"

10. Jurcsik, J., **Sódor, Á.**, Váradi, M., Vida, K., Posztobányi, K., Szing, A., Hurta, Zs., Dékány, I., Washüttl, A., Vityi, N. 2006, IBVS, 5709: „BVR_CI_C photometry of three RRab stars"

11. Jurcsik, J., **Sódor, Á.**, Hurta, Zs., Váradi, M., Szeidl, B., Smith, H. A., Henden, A., Dékány, I., Nagy, I., Posztobányi, K., Szing, A., Vida, K., Vityi, N. 2008, MNRAS, 391, 164: „An extensive photometric study of the Blazhko RR Lyrae star MW Lyr: I. Light curve solution"

12. Jurcsik, J., **Sódor, Á.**, Hurta, Zs., Kővári, Zs., Vida, K., Hajdu, G., Nagy, I., Dékány, I., Posztobányi, K., Koponyás, B., Váradi, M., Vityi, N. 2008, IBVS, 5844: „Multicolour CCD Photometry of Three RRab Stars"

13. Jurcsik, J., **Sódor, Á.**, Hurta, Zs., Kővári, Zs., Posztobányi, K., Vida, K., Hajdu, G., Nagy, I., Koponyás, B. 2008, IBVS, 5846: „Multicolour CCD Photometry of Four RRab Stars"

14. Jurcsik, J., **Sódor, Á.**, Szeidl, B., Kolláth, Z., Smith, H. A., Hurta, Zs., Váradi, M., Henden, A., Dékány, I., Nagy, I., Posztobányi, K., Szing, A., Vida, K., Vityi, N. 2008, MNRAS, közlésre elfogadva: „An extensive photometric study of the Blazhko RR Lyrae star MW Lyr: II. Changes in the physical parameters"

15. Jurcsik, J., Hurta, Zs., **Sódor, Á.**, Szeidl, B., Nagy, I., Posztobányi, K., Vida, K., Dékány, I., Váradi, M., Hajdu, G., Kővári, Zs., Kun, E. 2009, MNRAS, beküldve: „An extensive photometric study of the Blazhko RR Lyrae star, DM Cyg"

16. Kun, E., **Sódor, Á.**, Jurcsik, J., Hurta, Zs., Nagy, I., Kővári, Zs., Posztobányi, K., Kovács, G., Vida, K., Belucz, B. 2008, IBVS, 5859: „Multicolour CCD Photometry of Three RRab Stars"